# RISKS AND BENEFITS OF BUILDING THE SUPERCONDUCTING SUPER COLLIDER

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Congressional Budget Office

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## NOTES

Details in the tables may not add to totals because of rounding.

All years in this report are fiscal years, unless otherwise noted.

All costs are given in constant fiscal year 1988 dollars, unless otherwise noted.

Cover photograph courtesy of the Fermi National Accelerator Laboratory of Batavia, Illinois. The photograph shows a particle interaction in the 15-foot bubble chamber at Fermilab.

## PREFACE

The Superconducting Super Collider (SSC) is a proposed new particle accelerator, which would advance the state of high-energy physics. The next Congress will be faced with the choice of whether to begin construction of the accelerator, pursue an alternative, or defer the decision until further research reduces current technological uncertainties. In response to a request from the Senate Budget Committee, this special study analyzes the potential risks and benefits of building the SSC. In keeping with the Congressional Budget Office's (CBO) mandate to provide nonpartisan analysis, no recommendations are made.

Philip Webre of CBO's Natural Resources and Commerce Division, assisted by Kuljeet Kalkat, wrote this report under the supervision of Elliot Schwartz. Everett M. Ehrlich provided valuable assistance in the initial phases of the project. Robert Hunter, Director of the Department of Energy's Office of Energy Research, and Robert Diebold and the Staff of the Department of Energy's SSC Division provided many helpful suggestions and comments. The author wishes to thank Norman Blackburne, Judith Bostock, Desiree Di Mauro, Daniel Kaplan, Leon M. Lederman, Paul Maxwell, David H. Moore, Wolfgang K. H. Panofsky, Christopher Quigg, Robert L. Riemer, Burton Richter, Benno Schorr, Robert Siemann, Michael Sieverts, W. Edward Steinmueller, R. William Thomas, and Stanley Wojcicki for their helpful comments. Amanda Balestrieri edited the manuscript. Margaret T. Cromartie, Patricia Joy, and Gwen Coleman typed the many drafts, and Kathryn Quattrone and Nancy H. Brooks prepared the report for publication.

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## SUMMARY

To preserve the momentum of high-energy physics research in the United States, the Department of Energy (DOE) is planning the construction of a particle accelerator--the Superconducting Super Collider (SSC)--that has higher energy levels than the current generation of accelerators. The Congress has thus far appropriated $205 million for the SSC, including $100 million for fiscal year 1989, mainly for research and development (R&D) and associated equipment. The construction of the SSC, not yet approved, will cost much more: DOE estimates the total costs for the SSC and associated facilities will be $5.3 billion in current dollars (in fiscal year 1988 dollars, the estimate is $4.4 billion).

DOE is scheduled to recommend a site for the SSC in November or December of this year; the Administration may ratify this choice or leave the decision to the incoming President.[1] In any event, the next Congress is likely to be confronted with the choice of whether to appropriate funds for construction. Actual construction of the SSC is scheduled to take eight years, barring any delays. This report analyzes the risks and benefits of budgetary choices facing the Congress.

## THE SUPERCONDUCTING SUPER COLLIDER

The purpose of the SSC is to investigate the basic nature of matter without the expectation of any near-term use of the results. Over the decades, physicists have developed a "standard model," which explains a great deal of the behavior of matter and energy in the universe. Despite its achievements in explaining such behavior, the standard model cannot be complete since it involves many arbitrary assumptions. By exploring higher energy levels, physicists hope to expand the model by discovering certain particles and phenomena that have so far existed only in theory.

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1. The finalist sites are located in seven different states: Arizona, Colorado, Illinois, Michigan, North Carolina, Tennessee, and Texas.

The size and strength of the SSC are largely determined by the high energy levels needed to see the phenomena of current scientific interest. It is designed to contain two proton beams, each with an energy of 20 trillion electron volts. The most powerful facility currently in operation in the United States at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, has an energy of 0.9 trillion electron volts per beam. At 53 miles in circumference, the SSC's racetrack-shaped rings will be more than 10 times the size of the Fermilab facility and three times the size of the next largest accelerator currently planned.

At the heart of the SSC are two beams of protons circling in opposite directions in two intersecting rings, each composed of roughly 5,000 superconducting magnets. When the proton beams intersect in chambers called interaction regions, some protons from each beam will collide with some protons from the other, causing their constituent particles to interact. Specialized detectors will measure the energy and trajectory of these interactions and then store this information for later analysis.

## BUDGETARY ISSUES

DOE currently projects that the SSC will cost $4.4 billion in constant fiscal year 1988 dollars (throughout this report, all dollars are fiscal year 1988 dollars, unless otherwise noted). Construction of the accelerator itself accounts for roughly $3.2 billion (18 percent of which is designated for contingency costs), almost three-quarters of total project costs. The specialized detectors are projected to add $719 million, and research and pre-operating costs account for another $440 million. In addition, DOE estimates that the SSC will cost $270 million per year to operate. (These estimates were made before Congressional appropriations for fiscal year 1989.)

DOE states that its estimate is accurate within 10 percent, given that the site has not been selected and the final design studies have not been performed. Thus, the DOE estimate covers a range of $3.9 billion to $4.8 billion (see Summary Table 1). The relative certainty for each category of the estimate has not been published by DOE.

The Congressional Budget Office's (CBO's) technical analysis in Summary Table 1 examines the major components of DOE's current estimate for internal consistency. The lower bound of the technical analysis is well within the stated range of confidence for the DOE estimate, while the upper bound is $300 million above the range of confidence and more than $725 million above DOE's average estimate.

The historical analysis in Summary Table 1 simply takes the current DOE estimate and increases it by the average cost increase for accelerators built by DOE during the 1980s. DOE has built four accelerators in the 1980s and the average cost increase in constant dollar terms was 46 percent. Two of the accelerators were on budget and two suffered from exceptionally high cost escalation. No analysis of the cost increase for each category of the estimate was made because future cost increases may result from different sources.

SUMMARY TABLE 1. SSC BUDGET ESTIMATES
(In millions of fiscal year 1988 dollars)

| Category | DOE Analysis[a] | Technical Analysis[b] | Historical Analysis[c] |
|---|---|---|---|
| Construction | 3,210 | 3,210-3,480 | n.a. |
| Research and Development[d] | 274 | 274 | n.a. |
| Detectors | 719 | 890-1,175 | n.a. |
| Pre-Operating | 172 | 172 | n.a. |
| Total | 3,937-4,812 | 4,546-5,101 | 6,398 |

SOURCE: Congressional Budget Office, based on data from the Department of Energy.

NOTE: n.a. = not applicable.

a. Current estimates by DOE, made before Congressional appropriations for fiscal year 1989.

b. Adjusted by CBO for internal consistency.

c. Adjusted by CBO according to previous DOE cost performance. No component-by-component analysis was made because future cost increases may not result from the same sources.

d. Does not include $80 million in research and development performed between 1984 and 1987.

## Historical Cost Escalation as a Guide for the SSC

How relevant is the experience of building past accelerators? The final costs of the two immediate predecessors to the SSC--the Energy Saver and Tevatron I at Fermilab--were 64 percent and 122 percent, respectively, above their initial estimate. In another case (the Isabelle accelerator at Brookhaven National Laboratory), there were so many technical problems that the effort was abandoned before completion. On the other hand, DOE built Tevatron II and the Stanford Linear Collider with no, or only minor, cost escalation. Furthermore, much of the cost escalation occurred during the R&D phase, after the projects were authorized, but before actual construction began. Since the SSC's R&D program is well advanced, proponents argue, substantial cost escalation is unlikely. Much of the SSC technology was originally developed for the Energy Saver and Tevatron I, and this experience may help DOE avoid some of the cost escalation caused by difficulties with new technologies. The SSC is, however, much larger than those projects and has many more components, whose cost has escalated substantially with previous accelerators. Consequently, there is a high risk that the SSC will experience cost increases.

## Sharing the Cost of the SSC

Although DOE expects to receive $1.8 billion in funds from nonfederal sources to help defray the costs of the SSC, even proponents have called these assumptions overly optimistic. The most commonly discussed sources of cost sharing are the state in which the SSC is to be located and the international community. Several of the finalist states, most notably Texas and Illinois, have approved public funding to help defray construction costs should the SSC be located in their state. (The Congress instructed DOE not to consider such factors when recommending a site.) International sources have expressed interest in providing in-kind assistance with magnet and detector technology. But no prospective source has committed itself to major funding and the scale of anticipated funding is beyond the level of other countries' current high-energy physics budgets.

The Federal Budget for Basic Science

Since 1970, funding for high-energy physics has declined by 10 percent in real terms, although spending on high-energy physics has risen by 72 percent in real terms since its nadir in 1975. In 1988, high-energy physics received 6.6 percent of all federal basic science dollars, down from its 1970 high of 12 percent. By contrast, the 2,200 active high-energy physicists account for only about 3 percent of all active basic research scientists. Similarly, the 600 graduate students studying high-energy physics account for only 0.6 percent of Ph.D. students in science.

The SSC would consume a substantial portion of the current federal budget for basic science. Construction costs for the SSC will average roughly $600 million per year for a five-year period. By way of comparison, in 1988, all federal agencies spent $9.0 billion on all basic research and $4.5 billion on basic research in the physical sciences. The SSC would therefore account for 7 percent of the entire basic research budget and 13 percent of basic research for physical sciences for half a decade, assuming no increase in total basic research funding. In addition, the share of the science budget going to high-energy physics would be more than doubled.

## THE SSC AND ITS ALTERNATIVES

The SSC is not the only accelerator that physicists can use for their future research. The European Organization for Nuclear Research (CERN) has begun an effort to build a smaller accelerator called the Large Hadron Collider. Alternatively, physicists have also discussed construction of an electron-positron linear collider of intermediate strength in the United States.

Summary Table 2 permits a general comparison of the three major next-generation accelerators discussed in this report. The main points of comparison are cost, completion date, mass reach, and design risk. Costs are likely federal costs. The completion date indicates when the instrument is intended to become available for high-energy physics. Mass reach represents the energy level of the interactions or phenomena of scientific interest: only a fraction of the total energy from proton collisions can be used by science. Thus, while the SSC proton beams have a total energy of 40 trillion electron volts, the mass reach is only 3 trillion to 4 trillion electron volts. In Summary Table 2, mass reach is synonymous for the scientific potential of the instrument. The design risk is a qualitative assessment combining the current state of accelerator technology with the eventual ability of the instrument to perform as planned. The primary risk is not that the machine will not work, but rather that it will be less powerful or useful than its designers intend.

The SSC would be the most scientifically capable machine, but it is by far the most expensive of the near-term options. The Congress will have to decide whether the added scientific value and the lower design risk are worth the extra costs of $3 billion to $4 billion to U.S. taxpayers. Of the cost estimates, that of the SSC is most reliable: the

SUMMARY TABLE 2. COMPARISON OF MAJOR FUTURE ACCELERATORS

| | Superconducting Super Collider | Large Hadron Collider | Electron-Positron Collider |
|---|---|---|---|
| Estimated Cost to the United States (Billions of fiscal year 1988 dollars) | 4.5-5.1 | 0.6-1.0 | 1-2 |
| Completion Date | Late 1990s | Late 1990s | Late 1990s |
| Mass Reach (Trillions of electron volts)[a] | 3-4 | 1.0-1.5 | 1 |
| Design Risk[b] | lowest | high | high |

SOURCE: Congressional Budget Office.

a. Mass reach is related to energy and refers here to the scientific potential of each instrument.

b. Design risk is a qualitative assessment of the possibility that the accelerator will be less powerful or useful than originally planned.

others include estimates based on technology that is not yet developed. The SSC estimate is based on CBO's technical analysis of DOE's estimate. Others are constructed on the basis of reasonable assumptions.

The phenomena physicists seek to explain occur at mass levels of up to roughly 1 trillion electron volts (Tevatron I can reach roughly 0.3 trillion electron volts), and the next round of accelerators will therefore be evaluated on their ability to provide such a mass reach. Both the SSC and the Large Hadron Collider would provide more than enough energy to study the phenomena in which high-energy physicists are interested. All machines are intended to reach that level, but the electron-positron linear collider may be unable to explore phenomena completely at the upper reaches of that range. Nevertheless, the electron-positron linear collider stands a good chance of making substantial contributions to high-energy physics.

As a scientific instrument, the SSC seems to have the lowest level of risk of any of the alternatives, although it is far from riskless. The Large Hadron Collider will require superconducting magnets of unusual design with strengths that have not yet been achieved. Similarly, electron-positron linear colliders need substantial additional research before they can achieve this energy level. The SSC relies on technology that is more certain, but it has already benefited from $105 million in R&D for magnets and other components and will need almost $250 million more. The technology for the electron-positron linear collider might also make substantial progress with $105 million, or even $250 million, for R&D. (Current R&D funding for improving the designs of electron-positron linear colliders is less than $5 million per year.)

## CONGRESSIONAL OPTIONS

The initial choice before the Congress is whether or not to fund the construction phase of the SSC. If the Congress decides not to fund SSC construction in fiscal year 1990, it can choose to fund an alternative, either as a substitute or as a complement to further research on SSC technology. Options for a substitute facility include joining the effort by CERN to build the Large Hadron Collider. Alternatively, the Congress could fund research leading to the construction of an electron-positron linear collider of intermediate strength in the United States.

## Defer the Decision

The Congress has already postponed building the SSC this year. Recently, Frank Press, President of the National Academy of Sciences, suggested that actual construction might be deferred while magnet research is continued and until the current budget conflict is resolved.

The Congress could continue to defer its decision about the construction of the SSC. The advantages of deferral include short-term budgetary benefits (costly SSC construction would be delayed until later) and benefits from greater certainty about magnet technology (only two of the eight prototype superconducting dipole magnets DOE has built so far have been even partially successful). Furthermore, benefits are already flowing from the SSC superconducting magnet research program to industry. In addition, deferral could allow the Congress to continue funding research on the alternative collider options. Then, when the research on the various instruments is sufficiently mature, the Congress will be able to choose among them. There may be few costs to bear from a short delay: despite having been postponed for two years already, the SSC has not experienced a substantial real cost increase above the initial proposal. Furthermore, U.S. high-energy physicists will not be without work, since they are just now beginning to explore new phenomena with two new instruments that were recently commissioned.

On the other hand, deferring the SSC may in turn defer other high-energy physics projects, since DOE's budget may not be able to accommodate them all simultaneously. If the SSC is unlikely to reach the construction phase, it would be better to cancel it sooner rather than later. Deferral of the decision to cancel would only commit valuable resources to a wasted task.

## Build the SSC

Unless there are delays in the schedule, the SSC will set the most rapid pace of any of the alternatives in terms of providing access to high energy levels and hence potential scientific discoveries. The Congress must decide how much it is willing to pay to speed up discoveries in high-energy physics. The high-energy physics community in the United States wants to set a rapid pace, but it could continue to flourish even if the Congress chooses to fund high-energy physics at a slower pace.

The primary scientific risk of the SSC is that the large increases in the science budget needed to pay for the SSC may cause neglect in other basic science areas. (This concern will be great with regard to other physics research, especially research in other areas of high-energy physics.)

The construction of the superconducting magnets may improve the manufacturing technology for low-temperature superconductors. If there are new uses for low-temperature superconductors that would be encouraged by lower production costs, superconducting magnets may well move beyond their traditional markets in research and medical instruments. At the moment, there do not seem to be many such uses.

Low-temperature superconductor technology developed for the SSC is unlikely to contribute to the development of high-temperature superconductors. Building the SSC superconducting magnets will improve skills that may simply be irrelevant to the new high-temperature superconductors. Furthermore, deferring construction of the SSC until it can be built with high-temperature superconductors is likely to postpone its construction for 20 years or more and is not likely to save much money, if any.

### Join CERN in Building the Large Hadron Collider

The United States has been informally invited to join in the process of planning and building the Large Hadron Collider (LHC), CERN's next generation accelerator. CERN is considering a proposal to build the LHC by adding a ring of superconducting magnets to the Large Electron Positron collider tunnel in Geneva, Switzerland. The CERN strategy is to build an accelerator of one-third the strength of the SSC, but still of sufficient strength to investigate the energy levels of interest and discover the phenomena that exist in this energy range, which may include many of the particles of interest. After this level has been explored, larger instruments, such as the SSC, could be built. Whether or not the U.S. government participates in the construction of the LHC, the U.S. high-energy physics community will be involved anyway, since they already participate in CERN projects.

Because the LHC proposal is at a much earlier stage than that for the SSC, the United States could influence its design substantially. CERN and its members have yet to commit themselves to its construction. U.S. participation would have to be negotiated in terms of the U.S. contribution, the role of U.S. scientists and DOE, and the rules for contract bidding by superconducting-magnet manufacturers and other component makers in the United States.

Preliminary cost estimates suggest that the LHC will cost at most $2.4 billion to $3.1 billion. The U.S. contribution would depend on the outcome of negotiations with CERN on U.S. participation. Assuming the U.S. share is in the range of 25 percent to 33 percent, the LHC would cost U.S. taxpayers between $600 million and $1.0 billion, a savings of $3.5 billion to $4.5 billion relative to the $4.5 billion to $5.1 billion required by the SSC.

The principal scientific benefit of the LHC would be to permit U.S. high-energy physics to explore new energy levels at a lower cost than the SSC. But the LHC has lower energy levels than the SSC, which may preclude observation of some additional interesting phenomena. There would also be one less instrument worldwide, meaning that fewer experiments could be performed, and more of the available instrumentation would be concentrated in one location in Europe. Moreover, building the LHC instead of the SSC or an electron-positron linear collider would leave the United States without a state-of-the-art particle accelerator.

The principal technological benefits of the LHC should come from the cross-fertilization of European and U.S. manufacturing techniques for magnets and other components, assuming that negotiations solve conflicts in international contract bidding. But some of the technology benefits that might result if the United States pursued the SSC alone would be reduced. However, if CERN pursues the LHC without U.S. participation, many technology spinoffs would be worldwide anyway. Other technological outcomes will depend on the negotiations about

U.S. participation: unless U.S. superconducting magnet makers and other component suppliers receive contracts, there would be few spinoffs for U.S. industry. Moreover, because the LHC would be located in Geneva, Switzerland, there would be no local spinoffs for the United States.

Since it is limited by the size of existing facilities, the LHC must make more technical compromises than the SSC. Its very strong superconducting magnets are just beyond the capability of current technology and are of an unusual design. Furthermore, the LHC might have to be run at a very high collision rate, one that current detector technology cannot capture. Thus, the LHC has a greater degree of design risk associated with it than does the SSC. The LHC would share the Large Electron Positron collider tunnel, and, therefore, these machines might conflict with each other for experiment time and repairs. In addition, because there would be only one large machine worldwide, malfunctions could stop all work at the highest energy levels until fixed. Lastly, the European members of CERN might decide not to fund the LHC, leaving the Congress in its current dilemma.

### Build an Electron-Positron Linear Collider

The SSC and the LHC both work using high-energy proton beams. For technical reasons, accelerators that use electrons and positrons need less energy to study the same phenomena. This feature could eventually allow electron-positron linear colliders to achieve energy levels above those feasible for proton-proton accelerators, prompting some to suggest that an electron-positron linear collider be built instead of the SSC. Such a machine would be a larger version of the recently commissioned Stanford Linear Collider. While the DOE panel on alternative accelerator technology found that it would be at least 15 to 20 years before such an accelerator could match the capabilities of the SSC, it suggested that an intermediate-energy machine, perhaps approaching the mass reach levels of the LHC, could be researched, designed, and built within the next 10 years. Such a machine is not feasible or cost effective given current technology, but DOE has a major R&D program to enhance electron-positron linear collider technology. Whether or not the SSC is built, it is clear that, barring breakthroughs in technology, the proton-proton technology it